CHAPTER 6

SOLID EARTH SCIENCE

6.0 INTRODUCTION

From a geophysical perspective, Earth is unique among terrestrial planets in that it is a dynamic system that contains abundant water and also supports life. Earth has profoundly evolved over the 4.5 billion years of its existence, constantly reforming its surface and overturning its interior with a vigor that is often disruptive to the life it supports. The basic structure of the Earth's interior was understood in some detail by the end of the 1930’s; it was known that the planet has a metallic core, surrounded by a mantle of dense minerals, then by a less dense crust, and finally by thin oceanic and atmospheric layers. Yet the fact that every one of these components is in motion, manifesting a vast range of velocities over a diversity of scales, has only been known since the 1960s. A fundamental question is whether the distinctive dynamism of the Earth’s interior has been a key influence in the continued presence of water and the development of life or, conversely, the presence of water had a controlling effect on the mechanical properties of rocks and the Earth's dynamics. To address this fundamental question, we must understand the mechanics of the Earth’s interior and surface, and governing mechanical, physical and chemical processes.

Observations made solely from the Earth’s surface had long hobbled scientific imagination. Gazing on quiet landscapes, the human perception of the Earth's dynamism was restricted to infrequent catastrophes - violent earthquakes, volcanic eruptions - or low key but persistent erosion processes. Today, the global perspective from space offers a new outlook, a planetary reference frame from which to precisely determine the slow overturning motion of the mantle; to observe the planet's magnetic field fluctuating with the turbulence of its liquid metal core; to measure changes in the length of day forced by ocean currents and global winds; to watch how continents strain in anticipation of an earthquake or volcanic eruption.

NASA’s Solid Earth research program (NASA, 1991) examines the dynamics of the solid Earth at virtually all spatial and temporal scales, and aims to establish the scientific basis for reconstructing Earth’s past history and predicting its future evolution. The overarching goal is to observe and understand the fundamental properties and processes of Earth’s interior and crust which make it dynamic. The same effort also provides essential information to guide decision-making on issues of great human import by illuminating society’s vulnerability to natural hazards.

NASA’s objective in this domain is to contribute to scientific understanding and to provide technical leadership through pioneering space geodesy and remote sensing programs. The program requires highly accurate geodetic measurements to monitor the terrestrial reference frame, precise measurements of the static and time-dependent components of the Earth’s gravity and magnetic fields, and observations of the Earth's surface geology, topography, and deformation with time. The program will improve the understanding of dynamical processes in the solid Earth and their interactions with other elements of the environment, including impacts on human societies and the assessment of vulnerability to natural hazards. In fact, the solid Earth science element is fully integrated with NASA's Natural Hazards program, as part of the overall "Solid Earth and Natural Hazard Program" of the Earth Science Enterprise. The scientific research effort is comprised of two major components:

- Understanding the fundamental geophysics and geodynamics of the Earth’s interior and,

- Understanding global geological processes that shape the topographic surface of the Earth.

6.1 MAIN SCIENCE QUESTIONS

While geological and geophysical observations during the 20th Century have provided the general framework for understanding the nature of the Earth's interior and crust, they have left many fundamental questions unanswered about the physical properties of the inner components, that can be approached from a diversity of disciplines, including seismology, geodesy, geophysics and geochemistry, geologic mapping, sedimentary analysis, and laboratory studies. Within this multi-faceted research effort, NASA scientific activities focus on two main scientific questions:

- ***What are the motions of the Earth and the Earth's interior, and what information can be inferred about Earth's internal processes?***

The basic structural model of the Earth's interior, featuring a crust, mantle and solid/liquid core, largely evolved from the study of seismic waves. Owing in part to space-based measurements of contemporary crust motion and deformation, the plate tectonics model has become widely accepted, introducing the concept of rigid lithospheric plates that override the deformable interior (asthenosphere). Convection, governed by gravitational forces, is the accepted mechanism by which the mantle transports heat from the interior and drives plate motion. Despite this qualitative understanding, quantitative knowledge remains limited because the model is based largely on data describing millions of years of geologic evolution with relatively poor temporal resolution.

To gain a quantitative and predictive understanding of the mechanics of the Earth's interior, it is necessary first to infer internal heat sources and properties: temperature, viscosity, density, chemical and mineral composition. Fundamental knowledge is also needed of electromagnetic forces governing magnetic field generation, the coupling between mantle and crust, the physics of crustal deformation, the horizontal and vertical scales of convection, the time scales of change in convective motion, the role of chemical reactions and mineralogical transformations. Addressing these scientific issues requires studies combining laboratory investigations, numerical modeling, and a wide variety of observations taken on the ground, on ships and aircraft, and in space. NASA geodetic and geophysical measurement programs are part of a broad interdisciplinary effort to understand Earth's interior dynamics.

- ***How is the Earth's surface being transformed and how can such information be used to predict future changes?***

A conceptual understanding of the processes that have shaped the Earth's crust and topography has evolved from the recognition of influences from the Earth's interior, atmosphere, and hydrosphere. The present-day topographic surface of the Earth records the history of competition among sedimentation, erosion, land sliding, subsidence, sea level change, rock weathering, tectonics, earthquakes and volcanic eruptions. Surface topography also defines the boundary where the solid Earth interacts with the atmosphere, hydrosphere, and biosphere. The relative importance of the various landscape-forming processes, their interactions, and their time- or space-variability remain subjects of debate. Furthermore, their place in the evolution of the whole Earth, their effect on crustal deformation and mantle convection, and their role in the chemical differentiation of the planet remain uncertain. In addition to these fundamental geological questions, precise knowledge of surface topography and estimation of future changes are very important pieces of information for the pursuit of other environmental sciences such as hydrology, oceanography, and glaciology.

NASA's special contribution to this field of science is an integrated scientific approach, combining the application of global imaging and space-based geodesy with Earth system modeling. NASA's unique observing tools permit large-scale measurements, support quantitative analysis, and provide a global perspective that allows comparison among different regions of the planet. In addition, NASA is the source of fundamental geodetic reference data for a number of global programs in the US and internationally.

6.2 SCOPE AND NATURE OF THE PROBLEM

For convenience, the subject matter has been organized in the following two sections, recognizing that scientific problems may not necessarily fit exactly these categories. For example, topography expresses the integrated result of mantle convection and large-scale plate tectonics (solid earth dynamics), in addition to surface geological processes (weathering, erosion and sedimentation).

6.2.1 Solid Earth Dynamics

New and emerging insights into the internal workings of our planet result, in large part, from the analysis of simultaneous Earth gravity data, magnetic field measurements, and dynamic properties inferred from satellite observation. Although we now appreciate the intensity and ubiquity of circulation within the solid Earth, important features are yet to be fully understood. We do not yet understand whether mantle convection is layered or spans the whole depth of the mantle. We also aim to understand how mantle convection is coupled with the crust, and how gravitational (buoyancy) forces govern mantle convection that drives plate motions. The solid Earth holds many mysteries. Why are the inner and outer core rotating at different rates? What mechanism generates the magnetic field and why does the magnetic field, which remains relatively constant for hundreds of thousands of years, suddenly change and reverse its polarity? No single technique could provide enough information to solve these complex issues. A comprehensive approach, combining gravity and geomagnetic field measurements from a number of different sources with integrated global analysis and modeling, appears the most promising scientific strategy at this stage.

Changes in Earth's Rotation as a Measure of Fluid Motion in the Earth Interior

Until recently, interactions between the solid earth and the fluid core were a topic of speculations unconstrained by observation. That situation has changed, in part, because space geodetic measurements are now capable of detecting the signature of these interactions as changes in the rotational rate of the Earth as well as the position of the rotation axis within the Earth and with respect to inertial space. These observations also record momentum exchanges among the solid Earth, oceans and atmosphere, and the Moon, thereby contributing to understanding the structure of the core-mantle boundary, angular momentum changes due to core fluid motion, the nature of solid inner-core rotation, ocean and solid body tides, and liquid core oscillations.

Gravity Driven Mantle Convection

Departures of the Earth's gravity from the simple field of a homogeneous fluid rotating body are dominated by density variations related to convection. Thus, in addition to the basic configuration of crustal plates, oceanic ridges and trenches, the gravity field carries key information about the mechanics of mantle convection. At the moment, there is poor understanding of the relative roles of deeply penetrating "whole mantle" convection versus relatively shallow layered convection, and the horizontal scales of mantle convection cells. It is possible to estimate crustal thickness and infer physical properties such as lateral and vertical variations in viscosity and shear strength, by combining gravity data with information on deformation rates derived from space geodesy and topography data.

Magnetic Signature of Core and Lithosphere Properties

The existence of a magnetic field and its occasional polarity reversals have considerable theoretical interest in their own right (NRC, 1993). In addition, the magnetic signal provides insight into the internal structure, composition, and dynamic properties of the Earth's interior and the planet's ionized environment. The field near the Earth's surface is the sum of a main field generated by a fluid dynamo mechanism in the liquid core, remnant fields frozen in the crust, induced fields in the lithosphere, and field caused by time-varying external electric currents. It follows that, in order to interpret magnetic field observations, one must understand the main, remnant, and induced field components separately, and learn about the Earth's dynamics from each. The main field is virtually our only window on the workings of the liquid metal outer core, and its interactions with the solid inner core and the surrounding mantle. Changes over time measure core flow and are reflected, via core-mantle coupling forces, in Earth rotation changes. Numerical modeling of the complicated physics governing the core dynamo mechanism now provides a means to investigate the relationships between magnetic field, core flow, and earth rotation changes. The crust's remnant field records past magnetic field polarity reversals, the effects of plate tectonic motion, and the thermal history of the crust, but the physics governing these phenomena remain unknown. Induced fields provide information to improve the understanding of electrical conductivity, temperature and mineral composition of the mantle.

Large-Scale Deformation as a Measure of Mantle Convection

The plate tectonics model successfully explains many large-scale features of the crust, like mid-ocean ridges and ocean trenches, but fails to account for the distributed deformation field at plate boundaries, explain major earthquakes in plate interiors, and provide a complete description of vertical motions of the crust. This is largely because plate tectonics relies on evidence that is millions of years old and has poor temporal resolution. Further progress is expected from improved understanding of the Earth's contemporary dynamism and observations of crustal deformation at millimeter precision. The development of space geodesy, pioneered by NASA over the past two decades, provides this capability. NASA's space geodesy program has become the foundation of an international effort to measure the motions of the lithosphere and map the deformation of Earth's crust in three dimensions over time scales ranging from hours to years. The goal of these programs is to develop new comprehensive models of crustal motions that incorporate distributed plate deformation and take into account coupling to the underlying mantle flow. These models are expected to predict both horizontal and vertical motions and provide the mathematical framework for understanding earthquakes, volcanism, and landscape evolution.

6.2.2 Topography and Surface Change Processes

The processes at work within the Earth are manifested at the surface by changes in topography. Constructive processes, such as mountain building, earthquakes and volcanism, are balanced by erosion processes, giving rise to the landforms which provide the context for our daily lives. Understanding how these landforms originate and change provides insight in the ways human societies could accommodate to the changing landscapes.

The balance between accretion and erosion processes is, in itself, an important issue which warrants further investigation. How is this balance achieved and how does it evolve under varying climate conditions? What are the feedback mechanisms: how does climate affect erosion; how does erosion affect topography; how does topography affect climate? How do tectonics, erosion, and climate affect the course of rivers, their sediment load, and the evolution of beaches? How will sea-level rise or land subsidence affect this process? How can the geologic record of landforms be used, in combination with geodetic measurements, to quantify the frequency of seismic or volcanic events, assess their hazard potential, and consider human vulnerability to such geologic phenomena? While scientific insight can be derived from studying each of these events singularly, a globally integrated approach will provide understanding of their interactions and combined effects on the formation of the Earth's surface, as well as clues about the interior dynamics of the Earth.

Local Deformation and Earthquakes

Plate tectonics models can explain many large-scale features of the crust, as well as the observed large-scale motions of the Earth's surface. Detailed spatial and temporal distribution of strain within deformation zones and plate interiors can now be measured, but understanding the evolution of strain throughout the entire earthquake cycle remains a scientific challenge. Knowledge of the detailed development of topographic features, and their relationship to erosion, sedimentation, earthquakes, landslides, and surface geology, is necessary to understand the evolution of small- to intermediate-scale crustal features. Using space-based measuring techniques, it is now possible to monitor crustal deformation with millimeter accuracy, on spatial scales of meters to kilometers and time scales from minutes to years. This new observing capability fills the scale gap between traditional geologic mapping (motions on scales of hundreds of kilometers and millions of years) and the observation of catastrophic processes such as earthquakes (scales of meters and seconds). Natural laboratories, e. g. the distributed shear zone across Southern California, can serve as testing grounds for quantitative modeling of topography evolution, in addition to providing essential scientific data bases for earthquake vulnerability assessments.

Landscape Evolution

The forces that reshape the Earth's surface include sediment transport by wind and water, landslides, glacier erosion and transport of debris, volcanic eruptions, earthquakes and other tectonic motions. In addition, variations in the fluid content of sediments, due either to changes in ground water storage or to human activities (e. g. oil pumping), are often responsible for the measured vertical motions. Understanding the rates and magnitudes of these changes is challenging, but necessary if scientists are to predict the effects of natural or human-induced processes. Scientific understanding of sediment budgets, the impacts of severe storms, floods or human activities, and other processes related to landscape evolution, requires both a detailed view, obtained from field studies, and a macroscopic view provided by space observation. In addition, the perspective of space allows analysis and intercomparison of geologic features on a global scale, and often reveals spatial patterns that are not evident from the ground.

Global Sea Level Variations and Coastal Geomorphology

Global sea level has changed dramatically over the recent past, rising 100-150 meters since the end of the last ice age about 10,000 years ago, and continuing to rise today at a rate exceeding 1mm per year. Sea level change is a global environmental issue with many scientific and public policy aspects. The science issues are twofold. The first problem is that of understanding solid Earth processes and geodynamic properties that create tectonic motions at the locations of tide gauges, such as post-glacial rebound (creep in the mantle in response to the geologically recent melting of the northern hemisphere ice sheets) and determine the shape of marine basins. The other problem is that of understanding the influences of sea-level change on coastlines, through the analysis of coastal landforms and their change over time.

Global Volcanism

From the "Ring of Fire" around the Pacific to the Antilles arc in the Atlantic, volcanoes are part of the natural landscape, and offer opportunities to investigate some of the forces that both form or reshape the surface and present hazards to humanity. From a scientific perspective, it is important to understand the cycles of volcanic activity and the relationship between eruptions and landscape formation. There is both scientific and practical value in observing changes in volcanoes during the days, weeks, or months prior to an eruption, using available measurements of surface deformation, seismicity, and gas emissions. Observing transient signals is a challenging task, because only one fifth of the 600 or so active volcanoes on Earth are routinely monitored, even in the most rudimentary way. Space-based observations, including radar or lidar mapping of surface deformation, GPS arrays, remote sensing of gas plumes and surface temperature, offer the only practical means to monitor all active volcanoes. In conjunction with seismic and other *in situ* measurements, space-based observation provide a powerful tool to investigate the physics of magma migration, the role of gases and other fluids in volcanic processes, volcanic deposits and their mobilization, and eruptive cycles.

EXPECTED SCIENTIFIC ACHIEVEMENTS

Question 1: What are the motions of Earth's interior and what information can we infer about internal processes such as mantle convection and the generation of the Earth's magnetic field?

Expected new knowledge in the next 5 years

- Identification of regions where large temporal variability or trends exist in the Earth's gravity field as a result of mass redistribution in the solid earth, atmosphere and oceans;
- Order-of-magnitude improvement in the international geomagnetic reference field model;
- Order of magnitude improvement in knowledge of the Earth gravity field and International Terrestrial Reference Frame, to serve as a baseline for determination of the vertical motions of the Earth's crust and oceans.

Expected new knowledge in the next 10 years

- Identification of sources of gravity variations and relationship to mechanisms for mass redistribution among the hydrosphere, lithosphere, cryosphere, and atmosphere;
- Quantitative estimation of momentum exchanges between the Earth's interior, oceans, and atmosphere that result in variations of the earth rotation rate;
- Structure and dynamics of the Earth's mantle and core.

Question 2: How is the Earth's topographic surface being transformed and how can this knowledge be used to predict future changes?

Expected new knowledge in the next 5 years

- Local distribution of strain in deformation zones using interferometric SAR and geodetic techniques and relationship with increased vulnerability to earthquakes;
- Baseline global topographic dataset for identification of significant geologic features on kilometer-scale;
- Relationship between fine-scale geologic features and erosion, sedimentation, earthquakes, volcanic eruptions, landslides, and other hydrologic and biospheric surface processes;
- Baseline global record of volcanic processes including thermal activity, outgassing, and surface inflation/deflation.

Expected new knowledge in the next 10 years

- Global observation of surface deformation through several earthquake cycles and/or volcanic events and interpretation of these measurements in term of local stress in vulnerable regions;
- Relationship between sea level change and land subsidence for determining the trend and impact of sea level variations on global coastal zone environment;
- Decadal evolution of dynamic global geologic systems and relationship to vulnerability to natural hazards, including flooding, volcanoes, earthquakes, landslides, and coastal erosion.

6.3 NASA PROGRAM ELEMENTS

The most successful strategy to understand Earth’s dynamism and its relationship to the atmosphere, oceans, and other elements of the Earth system is an integrated approach in which process models are constrained by data acquired from traditional field and laboratory investigations, within the regional and global frameworks provided by airborne surveys and space-based observation. The NASA research strategy aims to achieve fundamental scientific advances through leadership in observing techniques and Earth system modeling, in cooperation with other national and international partner agencies and scientific institutions. NASA’s strengths and principal contributions to this interdisciplinary research effort are global observation of geologic processes and the topographic surface of the Earth, precise geodetic measurements to monitor the terrestrial reference frame, and measurements of the static and variable components of the Earth’s gravity and magnetic fields..

Characterizing the Earth's motions, both the bulk motion with reference to the stars and internal motions, calls for a combination of geodetic measurements. Geodesy is the science of measuring the figure of Earth, its rotational motions, crustal displacements, and gravity field. Determining the Earth's motion with reference to distant astronomical bodies (quasars) is principally achieved through Very Large Base Interferometry (VLBI) techniques based on simultaneous observation of quasi-stellar sources by an international network of radioastronomy observatories. The precise shape and time-dependent deformation of the Earth surface can be determined directly by space geodesy techniques, including Satellite Laser Ranging (SLR) and the Global Positioning System (GPS). Obviously, the motions of the Earth's interior cannot be measured directly and must be deduced from the analysis of surface deformations combined with high-precision space-based measurements of the Earth's gravity and magnetic fields.

Improved understanding of the impacts of solid Earth processes on human activities and societies, particularly in relation to assessment and mitigation of vulnerability to natural hazards, is part of NASA's strategic goals. Available observations of suitable accuracy extend over a few decades at most and cover only a very short period of the Earth history. For this reason, the research strategy aims to sample key geophysical and geological phenomena over appropriate time and space scales (e. g., study of earthquake cycles in the Los Angeles Basin), develop data analysis schemes that allow interpolating between sparse observation sites and relatively short data records, and create models that can simulate the range of possible future events. This strategy again relies on an integrative approach combining all previously acquired measurements and, at the same time, improving measurement techniques to unprecedented levels of accuracy and spatial coverage in order to foster new scientific discoveries. The principal advances realized in the recent past are the acquisition of the first global radar maps of the planet, using space-based synthetic-aperture radar (SAR) systems, and the development of interferometric SAR data analysis methods that allow reconstruction of surface topography and measurements of surface motions with unprecedented precision.

6.3.1 SPACE GEODESY AND THE INTERNATIONAL TERRESTRIAL REFERENCE FRAME

In this section, the discussion of space geodesy will focus specifically on the study of the Earth's rotation and deformation. Geodesy provides not only an accurate description of the Earth's motions, but also basic information for a broad range of fundamental investigations of oceans, ice sheets, and the Earth internal structure. For example, a measurement of sea-level rise at the level of precision (a few millimeters per year) now achievable by radar altimetry has no scientific significance unless the geodetic reference frame is known with the same accuracy.

NASA's pivotal role in geodesy and geodynamics has followed from the unique capabilities of the agency for extremely precise geometric measurements from space (NRC, 1990). Space-based geodesy, or simply "space geodesy", developed over the past four decades as a natural outgrowth of observations made to track the orbits of the first artificial satellites in the late 1950's. Space geodesy now permits a determination of the Earth's orientation in space, expressed in terms of nutation, precession, polar motion, and length of day with precision (on the order of 1mm) many orders of magnitude better than conventional geodetic techniques based on stellar astronomy and optical surveying. NASA's space geodesy program includes Very Long Baseline Interferometry borrowed from radio-astronomy, precision satellite tracking based on satellite laser ranging, and positioning based on the radio-navigation Global Positioning System. Radar altimetry of the ocean surface and Synthetic Aperture Radar (SAR) interferometry are also utilized; the former is discussed in the Global Ocean Circulation and Sea Ice section of this plan (section 5.3.1), while SAR interferometry is discussed in the Global Geology section (6.3.4).

Space geodesy measurements provide unique and truly global diagnostics of the Earth's fluid motions (oceans, atmosphere, mantle, and core) over a very broad range of time scales, from tidal to tectonic. Short-period (seasonal and interannual) signals are mainly associated with the atmospheric circulation. Changes in oceanic circulation and land hydrological processes (including snow and ice accumulation) can be detected on time scales from days to decades and beyond. Mantle convection, post-glacial rebound, and episodic violent phenomena such as earthquakes and volcanic eruptions produce signals on time scales from seconds to millions of years. Finally, material flow in the fluid outer core of the Earth and the relative motion of the solid inner core induce observable geodetic signatures at periods of a few years and longer. The key scientific problem is: *how effectively can the contributions from different processes in the Earth system be separated and, once separated, how can geodetic measurements be used to improve the understanding of each individual process?*

The challenge of geodesy is not only to make precise measurements of instantaneous positions but to also provide a stable reference frame against which to compare measurements such as sea level over decadal and longer time scales. The problem of fixing a reference frame is complicated by the forces both internal and external to the Earth which induce meter level changes in the location of the rotation poles, centimeter level changes in the center mass of the Earth and centimeter level motion of the land masses. NASA with other international partners supports the International Terrestrial Reference Frame (ITRF) project, organized under the aegis of the International Association of Geodesy, whose goal is to determine a global reference frame at the 1 millimeter accuracy level. NASA, in cooperation with the US Navy, is the principal contributor of precision observational data from its space geodetic networks, data archives and analysis centers, and provides technical and organizational leadership for the implementation of the project. The ITRF provides the data basis for investigating effects such as mantle convection, crust-mantle interaction, earthquake-related deformation, post-glacial rebound, dynamic ocean topography such as El Nino and the measurement of ice cap variability. The ITRF has also many practical uses: definition of a universal framework to which the operational Global Positioning System

(GPS) is connected, basic reference for the geographic coordinates used in land surveying, and precise orbit determination for satellite altimetry missions. The ITRF is determined from a few hundred reference points forming an irregular global network of non-uniform quality, providing daily determinations of the Earth's rotation parameters and annual estimates of deformation rates. Geodesists have recently noted that improvements in precise orbit determination and station positioning are slowing and we that the present technologies may be reaching a noise floor. Because scientific discovery in Earth science is predicated to a large extent upon improvements in positioning and timing accuracy, NASA's goal over the next decade is to advance space geodetic technologies with an eye toward millimeter or better positioning within an equally accurate and stable reference frame.

6.3.1.1 Systematic Geodetic Observation Programs

VLBI International Network

VLBI is the only technique capable of continuously determining the Earth's orientation and rotation rate (length of day) relative to inertial space. VLBI therefore provides the critical data to determine the long-period motion of the Earth's rotation pole and rotation rate and to provide long term stability for satellite orbits such as the GPS constellation or the LAGEOS geodetic satellites so important to the maintenance of the ITRF.

Because of VLBI's unique capabilities, NASA will continue to improve VLBI technology with the goal of higher precision and accuracy for the terrestrial reference frame. By the end of calendar year 2001, NASA and cooperating federal and international agencies will have completed a decadal program to improve VLBI observations using the Mark IV technology with a five fold improvement in sensitivity. The International VLBI Service (IVS) from its central bureau at the Goddard Space Flight Center provides the organizational framework for the international consortium of agencies participating in geodetic VLBI science. The IVS with NASA sponsorship has launched the CORE project (Continuous Observations of the Rotation of the Earth). CORE will engage over a dozen international partners in a program to use Internet and existing radio telescope facilities with the goal of achieving continuous operation of VLBI observations. In addition to more effective use of existing assets, CORE will demonstrate more cost-effective operation procedures and provide the required level of stability to enable monitoring Earth rotation over periods of several days. Beyond the year 2000, the main technical challenge will be the full automation of VLBI observations.

International Laser Ranging Service

SLR is the most accurate space geodetic technique available to measure the sub-decimeter scale motion of the Earth's center of mass. These displacements create a problem for global scale satellite altimeter missions such as TOPEX, Jason, and ICESat which cannot differentiate between a surface level change and a displacement of the Earth's center of mass. Sustained SLR observations of dedicated passive geodetic satellites like LAGEOS also provide essential information to determine the long-to-intermediate wavelength components of the Earth's gravity field and identify time-dependent gravity variations as envisaged in the forthcoming series of gravity mapping missions (see section 5.3.2). Individual range measurements from the best sites among a global network of nearly fifty SLR stations are accurate at sub-centimeter levels.

The Central Bureau for International Laser Ranging Service (ILRS), a service of the IUGG located at the

Goddard Space Flight Center coordinates and supports the efforts of numerous international SLR stations, and insures the quality of SLR observations and products. Continued development may reduce uncertainty below one millimeter over the next decade, but even more significant improvement would result from better geographical coverage of the globe. On a longer time scale (2003 and beyond), NASA plans to develop and deploy the SLR2000 equipment, a fully automated satellite ranging system capable of autonomously implementing a pre-programmed measurement sequence and reporting data over the Internet. The goal of SLR2000 is to provide more accurate orbit determination through better site location and continuous, cost effective tracking technology.

International GPS Service

GPS receivers are required for many practical purposes such as aircraft instrument landing, coastal navigation, surveying, etc. NASA's goal over the next decade is to provide technical leadership and organizational linkages with the international community that will enable the use of these receivers for scientific as well as practical purposes. To this effect, NASA sponsors the operation of the Central Bureau for the International GPS Service at the Jet Propulsion Laboratory (JPL), as well as related scientific methodology and software development. Daily orbit solutions produced at JPL for the GPS constellation are used to improve the accuracy of GPS fixes by thousands of public and private users every month. These improved orbits, in turn, allow the GPS constellation to serve as a reference frame for precise orbit determination for missions such as SRTM, Jason, TOPEX, VCL, ICESat, GRACE, CHAMP, and others. As discussed in section 5.3.4.3, permanent ground-based arrays of precision GPS receivers are currently being developed by NASA in cooperation with local agencies and governments for a variety of applications. Developments will be pursued to progressively improve automation, accuracy, and integration of these receiver arrays for increased scientific value. GPS software and antenna developments will also be required to reduce vertical positioning errors, which are still at least an order of magnitude larger than the theoretical limit. NASA is also supporting the development of GPS based remote sensing technologies that include limb sounding of the ionosphere and atmosphere and GPS reflection studies for geodetic imaging of the Earth's surface.

In 2001, NASA will release its newly developed Global Differential GPS system (GDGPS) capability that provides 10 to 20 centimeter real time positioning anywhere within the GPS constellation. We anticipate that this system will ultimately provide 1 cm real time orbit solutions. This new technology will enable a host of new civilian, commercial, and scientific applications from precision landing to onboard satellite processing. In the coming decade NASA intends to continue the development of advanced technologies to improve the GPS system capabilities and to utilize the system for remote sensing of the Earth system.

6.3.2 Gravity Field Studies

While local measurements of gravity have been made at the Earth's surface for more than a century, meaningful global gravity models could not be inferred until precision tracking of artificial satellites began in the 1950's. Since then, many successive generations of gravity field models have been produced, providing practical returns to the space program in term of orbit determination, and yielding new insights about the Earth's mass distribution and related forces which control mantle convection and plate tectonics.

Traditionally, the gravity field has been treated as a static property of the Earth, and scientific interest has been focused on the description of the field and interpretation of departures from the gravity of a rotating homogeneous fluid. The static field is dominated by irregularities in the solid Earth caused by convective processes that deform the solid Earth on time scales of thousands to millions of years. Further improvements in the accuracy of static field measurements, expected from forthcoming satellite missions, will resolve small-scale features of considerable geophysical significance, such as the depth of continental roots, the base of "hotspot" convection plumes in the mantle, and the detailed structure of tectonic features such as subduction zones and ocean ridges.

The most dramatic scientific advances expected from the next generation of gravity mapping missions will come from the investigation of the very small part of the field which does vary with time due to mass redistribution processes acting on time-scales from hours to thousands of years. These include tides raised by the Sun and Moon, post-glacial rebound, changes in ground water storage or accumulation over land (snow, ice, and water bodies), sea-level change and variations in ocean circulation. Much of this new information has applications to problems of considerable societal importance such as climate change and the availability of natural resources. Using variations in the Earth's gravity field as a remote sensing tool is now widely accepted (NRC, 1997).

6.3.2.1 Systematic Earth Gravity Mapping Program

Several decades of satellite tracking and sea surface topography data have been archived and used to deduce progressively more accurate global gravity field models. The most advanced model yet developed (by NASA and other federal agencies) relies heavily on satellite tracking data, as well as land and ocean surface measurements, and satellite radar altimetry. NASA generally relies on other agencies for surface gravity measurements. Airborne gravimeter and gravity gradiometer measurements complement satellite data and provide critical information for resolving the very short scales that are important for ice sheet mass balance studies, for characterization of tectonic features, and for closing gaps in satellite coverage at high latitudes. NASA will continue to support surface and airborne gravity measurements when relevant to support satellite missions.

New satellites, flying at various orbital inclinations and altitudes, continue to provide unique new information on the Earth gravity field which do not supersede, but rather supplement data from past missions. Thus, NASA will continue to acquire precision satellite tracking data, launch new laser reflector satellites in cooperation with international partners, and incorporate GPS receivers as standard flight instruments whenever convenient. Each new gravity model makes use of all previous data, plus new information derived from SLR tracking data and on-board GPS determination of satellite position.

6.3.2.2 Experimental Space-based Gravity Measurements

A new phase is beginning with a series of experimental gravity mapping missions. The CHAMP mission, led by Germany with US participation, is based on tracking a low-orbit spacecraft (CHAMP) using radio-navigation signals from a high-orbit satellite constellation (GPS), leading to further improvement in knowledge of the long-to-intermediate wavelength components of the gravity field. The NASA Gravity Recovery and Climate Experiment (GRACE) mission will pioneer a more accurate low Earth orbit (LEO-to-LEO) satellite-to-satellite microwave tracking technique (Launch scheduled for late 2001). The GRACE low-altitude orbit (450 to 250km) and expected five-year lifetime will provide unprecedented measurement accuracy for both the static and time-dependent components of the gravity field.

The anticipated scientific returns of these technical advances have been detailed in the recent *Satellite Gravity and the Geosphere* report of the National Research Council (NRC, 1997). Gravity measurements, as implemented by the GRACE mission, are expected to quantify any increase in the total mass of the ocean to an accuracy equivalent to 0.1 mm/yr sea-level rise, fully one order of magnitude better than the rate observed over the last century (on the order of 1mm/yr). Gravity measurements by these satellite missions will reduce uncertainty in the knowledge of the geoid to the same level as ocean altimetry measurements (approaching 10mm accuracy) for spatial scales of 300km and larger over land (see section 3.3.2). Beyond the determination of the static gravity field, the GRACE mission will explore the feasibility of detecting changes in the distribution of oceanic water masses, a space-based measurement equivalent to that of ocean bottom pressure. The GRACE mission is expected to detect, over a period of several weeks, transient changes in land water storage equivalent to the accumulation of a 10mm water layer over an area of 10^6 km^2, a promising development for the study of the global water cycle (see section 2.3.2). Thus, ultra-high precision gravity measurements open a pathway to systematic observation of time-dependent gravity as a remotely sensed property of Earth.

Follow-on experimental gravity mapping missions using laser interferometry for satellite-to-satellite ranging, high precision laser cooled gravity gradiometers, and advanced on board accelerometers could provide improvements of one hundred to one thousand times in the resolution of the time variable gravity component. This quest for improved sensitivity in gravity field measurement should lead to the measurement of seismo-tectonic events on the ocean floor and the dynamics of continental collision, as well as ultra precise measurement of fresh water distribution on the continent, precise measurement of ocean heating, and ice cap dynamics.

6.3.2.3 Space Geodesy Data Analysis and Modeling

Fundamental scientific advances are anticipated with the development of fluid dynamical models of the Earth's interior that are consistent space-based gravity and geodetic measurements and other (geodetic, seismic, magnetic) data. The analysis of gravity data combined with other observations relative to mass redistribution potentially provide a powerful means to monitor a broad set of variable phenomena in the Earth system. This task places an unusually strong demand on computational resources, and an important element of the research program will be the development of fast algorithms and data processing schemes to deal with the enormous data volume and complex relationships between measurements and the geophysical quantities of interest. As space geodesy data (gravity, center of mass, earth rotation, site displacements) are representative of the mass distribution, they offer a means to observe the denser components of the Earth system from space. It is expected that geodetic time series of Earth orientation (polar motion, length of day, center of mass) and time-dependent gravity field data will be combined with other measurements to monitor the ocean circulation, hydrology, and ice sheet mass balance. Most significantly, the fusion of temporal variablity of gravity over the oceans and polar ice caps coupled with high accuracy geodetic ocean and polar altimetry could be used to determine the steric or heat induced component of sea-level change to provide an accurate global assessment of the ocean’s heat storage role.

6.3.3 MAGNETIC FIELD STUDIES

The magnetic field seen at the surface of the earth or measured by a spacecraft in low earth orbit is the sum of the main field generated by fluid motions in the liquid core, by remnant and induced magnetism in the lithosphere, and external fields produced by currents in the ionosphere and magnetosphere. For this reason, magnetic field observations are of interest both to NASA’s Earth Science Enterprise and the Space Science Enterprise. The magnetic field and its temporal variations are a fundamental property of the planet and provide deep insight into the structure, composition and dynamic properties of Earth and its immediate surroundings. Through its own sponsored activities and collaboration with other national and international agencies, NASA leads the development of geomagnetic field models for scientific and practical applications. Space borne magnetic field measurements provide us with the enormously improved spatial and temporal resolution required for global geomagnetic field models. Of special interest are the time variable components of the geomagnetic field. From a solid Earth perspective, these time variable sources come from within the Earth's geomagnetic dynamo within the core, from electric currents induced in the mantle, lithosphere and oceans by external field activity, and from within the lithosphere due to variations in lithospheric stress and associated variations in conductivity.

A major objective of the geomagnetic field program is understanding the mechanism(s) in the Earth core that generate and maintain the main geomagnetic field and induce variations (including polarity reversals) over time scales ranging from years to thousands and millions of years. This fundamental problem relates to many unknowns: the nature of core-mantle coupling and boundary conditions, fluid flow in the outer core, and the detailed nature of 3-dimensional dynamo mechanisms. From the first observations of the secular variation of the geomagnetic field by Magsat in 1980 have come models of circulation within the Earth's molten core. The circulation models derived from these observations are now being compared to geodetic measurements of the Earth's rotation as well as surface deformation to understand previously unexplained phenomena. Magnetohydrodynamic models have only recently successfully modeled the self reversing phenomenon of the Earth's field and in the process suggested a higher rotation rate of the inner core than that of the Earth's mantle. In a dramatic statement for continued interdisciplinary modeling efforts, seismologists are debating the validity of seismic evidence supporting this inner core rotation anomaly. We have much to learn of the structure of own planet from studies of the geomagnetic field.

Of great interest to the surface change program are the smaller scale magnetic field variations that are associated with crustal magnetism. This anomalies and their time variations constitute a window for investigating the internal structure, composition and dynamics of the Earth's crust and mantle. Numerous laboratory and field measurements point to the possibility of geomagnetic and electromagnetic phenomena related to seismic events. Although we have yet to observe a significant level of reproducible results, geomagnetic field measurements including space based magnetotelluric experiments should be explored more vigorously because of the potential for significantly advancing our knowledge of earthquake and volcanic events.

6.3.3.1 Systematic Geomagnetic Observation Program

NASA undertook the pioneering POGO and MAGSAT missions which provided the first high-quality vector field measurements from space. Since the end of the MAGSAT mission in 1980, international partners have taken the lead for space-based magnetic measurements, with NASA's cooperation and support. Several upcoming missions, launched in 1999 and later years, will provide simultaneous observations from multiple spacecraft and allow improving the precision of magnetic field models. These missions include: Oersted (Denmark, February 1999), CHAMP (Germany, late 2000), and SAC-C (Argentina, late 2000). To complement this observational program, NASA maintains a magnetic modeling and analysis activity at the Goddard Space Flight Center, to provide processed field data to NASA investigators and scientific partners.

The primary observational requirement is continuous mapping of the geomagnetic field by satellites in configurations optimized to separate the various geophysical sources of the field. For example, external field studies are best served by measuring horizontal gradients at high altitude, while crustal field studies use vertical gradient data obtained from low altitude orbits. No single observing mission can satisfactorily discriminate between crustal, core-field, external field and electromagnetic induction, but each type of measurement contributes to advances made through combined analysis. Globally synoptic geomagnetic field measurements from a constellation of geomagnetic sensors could provide the improved separation of internal and external geomagnetic field sources required for lithospheric measurement and magnetelluric sounding. A key objective is to establish an orbiting array of accurate, high resolution vector magnetometers to measure both the external magnetic field and the related current systems.

We will continue to strive for a global constellation of geomagnetic instruments through the participation in international magnetic field monitoring programs. NASA will facilitate the placement of research-quality instruments on available flights of opportunity, as well as on dedicated joint missions with international partners whenever possible. Accurate, high resolution magnetometer systems are not presently suited to missions of opportunity due to their large mass, high power consumption and bulky designs. Technology development will be focused on non-magnetic star-tracker cameras for accurate attitude knowledge, miniature magnetometer arrays with adequate sensitivity and accuracy, and various electric field sensors. The availability of suitable measurement technology is currently limiting our measurement strategy.

6.3.3.2 Geomagnetic Data Analysis and Modeling

Numerical simulation of magneto-hydrodynamic activity in the Earth's core has been recognized as a grand challenge of physics throughout the 20th century, and some of these modeling efforts have been supported by the NASA program for high performance computation. Three-dimensional dynamo simulations have provided new insights into the Earth core dynamics, and will drive the development of better core field models. Improved methods for separating the crustal field will be developed, using synoptic satellite constellations, field gradient information, and refined models of the external field sources in the ionosphere and magnetosphere. NASA will continue to support further theoretical research and model developments, which are now beginning to generate realistic model fields with great promise from continued improvement.

6.3.4 GLOBAL GEOLOGY STUDIES

Global geology views the Earth landscapes as the outcome of many interacting processes involving the Earth's interior, surface hydrology, the biosphere and atmosphere. The NASA research program aims to develop fundamental understanding of these interconnected processes through the use of remote sensing data, field observations, and related data analysis and modeling activities. The program represents a natural springboard from which to launch application-oriented short-term studies focused on assessment of vulnerability to natural hazards such as floods, landslides and debris flows, coastal erosion, volcanic eruptions, and earthquakes. Fundamental understanding of landscape-forming processes is essential to reconstruct the history and evolution of dynamic geologic systems and thereby extend the time-frame far beyond the bounds of direct observation of contemporary phenomena. Detailed observations of the processes associated with natural hazards often exist only for a few decades, a time span much too short to encompass the range of hazardous events. Understanding the long-term behavior of natural systems is the pathway to assessing current risks of catastrophic events. Unraveling these interactions is a fundamental first step toward finding efficient ways to conduct human activities, taking into account available resources and potential hazards.

Tectonic Motion and Earthquakes

Local deformation and earthquake studies aim to understand and predict the behavior of earthquake fault systems. Intensive studies in areas such as the Los Angeles basin or the Tien Shan in China are conducted to deduce both the recurrence intervals and magnitudes of displacements along known faults, as well as measure and monitor the contemporary accumulation of strain. Buried faults are particularly challenging since they show no surface rupture and can only be inferred indirectly from geomorphic, stratigraphic, geopotential, and geodetic data. The principal NASA contribution is the measurement and interpretation of crustal deformation throughout the earthquake cycle (i. e., pre-seismic, seismic, and post-seismic periods) using space geodesy and remote sensing techniques, predominantly the Global Positioning System (GPS) and Synthetic Aperture Radar (SAR) Interferometry. These studies are usually performed in cooperation with other US and international organizations: the US Geological Survey, the National Science Foundation and many local agencies and organizations provide critical *in situ* observations and knowledge as part of various integrated research programs. A critical component to prediction of seismic phenomena is a more accurate knowledge of lithospheric rheology and stress. NASA provides the technological and scientific leadership in the development of space geodetic techniques to accurately map surface strain. We must now begin to focus our attention on new spacebased techniques to extend our knowledge of the state of the lithosphere.

Volcanism

Although volcanoes may lie dormant for centuries and become sites of intense human presence, they can erupt into catastrophic activity, sometimes on short notice. The problem is to identify the geologic properties and processes that govern the recurrence of volcanic eruptions, how eruptive events develop, and how past eruptions have affected the surrounding landscape. Many (perhaps most) volcanoes experience significant changes in the days, weeks or months prior to eruption, including surface strain, seismicity, ground temperatures, and gas emissions. Capturing these ephemeral signals can be challenging. Less than 20% of the 600 or so active volcanoes on earth are routinely observed. Systematic observation from space considerably enhances our capability to collect data that may be used to provide a long-term perspective on global volcanic activity. Remote sensing techniques provide only partial information that complements field data on the age, lava composition, sequence, and character of past eruptions, as well as structural aspects of likely eruptive sites. NASA’s main contribution over the next decade will be precision geodetic and topographic measurements, gas emission studies, and thermal monitoring coupled with data interpretation and modeling to understand the processes that produce and accompany eruptions. These studies are conducted in cooperation with the US Geological Survey and other Federal Agencies, and combined with international efforts.

Dynamic Geomorphology

The landscape has evolved over geologic and shorter time scales to produce the topographic surface we see today. Land-forming processes are governed by differences in rock strength, moisture availability, vegetation patterns, and slopes created by tectonic motions. In addition to the tectonic and volcanic processes discussed above, a number of competing land-forming processes modify topography, including sedimentation and erosion by river systems, land subsidence, coastal erosion and landslides. These processes are modulated by, and affect other components of the Earth system, the atmosphere, hydrosphere, and biosphere. Orographic effects on the atmospheric flow funnel precipitation on the windward side of mountain ranges and create rain shadows on the leeward side. Both the nature and rates of dominant erosion processes are tied to topography and rainfall. Gently sloping, vegetation-covered landscapes will change at rates and through processes, such as soil creep, that are very different from the bedrock landslides and debris flows that erode steep, sparsely vegetated slopes. While *in situ* observations yield insight in individual processes, remote sensing provides a regional perspective to view large-scale processes and multiple process interactions, as well as a basis for comparing these phenomena in different environments. NASA programs provide unique measurement and modeling capabilities contributing to the understanding of topographic evolution and landscape development. These studies have important societal implications as they provide a scientific basis for quantifying vulnerability to natural hazards related to land-forming, as well as human impacts on landscapes.

Sea Level Rise

The geologic record reveals that mean sea-level has varied considerably in the past from its present day position. Over the last 1.6 million years, sea level fell and rose repeatedly in response to the waxing and waning of large continental ice sheets in North America and Eurasia. Sustained intervals of warmer climate were always associated with a rise in sea level, as the volume of glacier ice was reduced and the oceans underwent thermal expansion.

Potentially the largest impact on global mean sea-level would be from the melting of polar ice sheets. The scientific challenge is to assess the mass balance of very large polar ice bodies and factor in geological processes, such as eustatic adjustment in the underlying continental basis. Regional "post-glacial rebound" can be as large as 50-100cm per century at some locations in Scandinavia. At present, the combined uncertainty on trends in the mass balances of the Greenland and Antarctic ice sheets is larger than uncertainty in sea level rise from all other causes. Even partial shrinkage of the polar ice sheets would inundate the major coastlines of the world and produce serious economic consequences. On shorter time scales, the 10 cm rise currently being anticipated in the next 30 to 50 years will threaten coastal wetlands, increase exposure to storm surges and wave damage, produce increased coastal erosion and allow substantial encroachment of salt water in near-shore aquifers. Numerous cities built near the sea-shore in regions subject to geological subsidence are now very sensitive to further sea level rise. New Orleans in Louisiana is already below high-tide levels.

6.3.4.1 Systematic Global Topography Measurements

The principal new tools brought by space-based observation to the study of global geology are the capability to deduce surface composition over large geographic regions using multispectral imaging and the capability to produce precise, high-resolution, global topographic maps. The first type of information is provided by a suite of past and current moderate-to-high resolution multispectral imaging radiometers, such as the Thematic Mapper on the Landsat series, and similar visible and near infrared instruments on the French SPOT satellite series. For geologic applications, basic imaging data have already been acquired for most of the world and the main issue is one of data access.

Topography is a fundamental geophysical parameter. Precision topography is a key observable for global geological studies, other fundamental scientific investigations (e. g. geodynamics, hydrology, ecology) and a wide range of applications, including the assessment of coastal and river basin flooding, volcano and earthquake hazards. Topographic information can be obtained by stereographic analysis of optical image pairs (e. g. SPOT), but the most capable remote sensing method is the technique of SAR interferometry using synthetic aperture radar (SAR) data. The NASA Shuttle Radar Topography Mission (SRTM) is the first high-resolution (30m horizontal, 16m vertical) near-global topographic mapping mission with full consistency to the global ITRF geodetic reference frame.

SAR interferometry can also provide extremely high vertical (or line-of-sight) accuracy for studies of surface deformation, subsidence, volcanic inflation/deflation, etc. This technique for studying tectonic deformation provides unprecedented high-resolution and spatially continuous measurements, at sampling intervals of tens to hundreds of meters over large regions, that could not be obtained efficiently by any other method. Regional deformation studies, that require long sequences of SAR data from precisely known trajectories, are currently conducted with data sets from existing SAR satellites (European ERS-1 and 2 tandem missions, Japan's JERS, Canada's Radarsat). These systems were not optimized for interferometric observation, however, and suffer from a variety of artifacts and processing-related problems that preclude routine utilization over large areas.

The highest priority requirement of global geology research is maintaining repeated or (ideally) continuous space-based SAR observation of the surface of continents for systematic analysis of surface deformation and changes in topographic features. A minimum of ten years of measurements is necessary to study important time-dependent phenomena or "cycles", such as postulated for earthquakes. The objective is to maximize the probability of capturing significant phenomena and assess the spatial and temporal variability of deformation rate over a period long enough to cover at least one earthquake cycle. These measurements must normally be combined with GPS geodetic reference points and GPS array data to supply *in-situ* reference measurements and provide a continuous temporal perspective.

The second priority is conducting periodic (at least every five years) global topographic surveys at 30m spatial resolution and 2-5 meters vertical accuracy. This objective can be attained by the regular SAR interferometric surveys (see Box 10) complemented by discrete high-precision altimetric data provided by satellite-borne lidars (see Box 8 for the ICESat terrain mapping mission and section 1.3.1.3 for the experimental Vegetation Canopy Lidar mission). The objective of the NASA global geology program is to increase the spatial resolution of space borne lidar surveys to 3-5 meters across a relatively large swath, while achieving sub-meter vertical accuracy, to enable two-dimensional mapping of *ground* topography below the canopy for geologic structure, in flood plains and coast zones to estimate risk.

Box 10
Topography and Surface Change Mission

Solid Earth research and polar sciences give highest scientific value to repeated (systematic) synthetic-aperture radar (SAR) surveys of land and ice surfaces, and tandem SAR missions, for differential interferometric reconstruction of surface topography and surface deformation over intervals of days (ice streams) to weeks (active tectonic regions).

The technical requirements for the mission include:

- High spatial resolution (of order 10-30m) SAR imaging system with multiple polarization capability,
- Dual frequency (L-band + second frequency) or wide bandwidth (for split frequency analysis), optimized for repeat interferometric observations and minimal phase decorrelation by ionospheric, atmospheric, and surface phenomena.
- Capability to complete, every five years, a global topographic survey with 30m horizontal resolution and 2-5m vertical accuracy, in addition to high-resolution (1-10m) mapping of selected sites for process studies.

NASA is examining potential private sector investments in global SAR observation systems that could provide the required scientific information through a data purchase.

6.3.4.2 Experimental Geologic Mapping Missions

Basic geological, soil, and vegetation information is currently inferred from high-to-moderate resolution spaceborne optical imaging systems operating in the visible, near and short-wave infrared, as well as thermal infrared. A new generation of advanced imaging instruments on the EOS Terra, Landsat-7 and New Millennium Program EO-1 missions (see section 1.3.1.3) will provide valuable information to address geologic applications. The experimental ASTER instrument on EOS Terra will provide the first spectrally resolved thermal image data that will enable determining the composition of silicate materials, studying volcano temperature variations, and producing geologic and geomorphic maps. Owing to their high spatial resolution, ASTER thermal infrared image data are also expected to capture variable SO_2 plumes emitted by active volcanoes. Currently, no ASTER follow-on is planned after the five-year Terra mission but similar observation capabilities may be available from commercial systems when the usefulness of ASTER-like measurements for global geology studies is established.

The New Millennium Program EO-1 technology demonstration will provide the first spaceborne visible/near infrared hyperspectral imaging capability, enabling identification of most rock-forming minerals and surface materials based on spectral reflectance characteristics. While EO-1 coverage will be extremely limited, similar capabilities will also be available from two other hyperspectral imaging demonstration missions (NEMO and Warfighter) planned by the U.S. Navy and Air Force. Still another hyperspectral imaging satellite mission (ARIES) is planned by Australia.

Beyond these ongoing projects, NASA will encourage experimental or technology demonstration missions to explore innovative remote sensing approaches that can address outstanding global geology issues. In particular, NASA is studying options for a differential SAR interferometry demonstration mission that could be a pathfinder for sustained measurements of this type in the future (see Box 10). Another example is high-resolution multispectral imaging from geostationary platforms for continuous observation of transient gaseous emissions from active volcanoes.

NASA will encourage instrument concept studies and development to fully exploit the potential of satellite remote sensing for geologic mapping of the Earth surface. An active experimental airborne observation program is planned as a means to develop and test innovative remote sensing techniques, perform critical site-specific surveys, and validate space remote sensing data. Prominent among current aircraft sensors are the high-resolution hyperspectral Airborne Visible and Infra-Red Imaging Spectrometer (AVIRIS), in addition to thermal infrared imager, such as the MODIS and the MODIS/ASTER Airborne Simulator instruments (MAS and MASTER), and airborne imaging radar (AIRSAR) and Lidar systems for high-resolution topographic mapping.

6.3.4.3 Geologic Field Studies and Airborne Observation Campaigns

The NASA global geology program utilizes "natural laboratories" distributed over the whole world to observe and study specific processes and acquire validation data for verification of satellite measurements. For example, the western U.S. Cordilleras, the Himalayas including the Tibetan Plateau, and the high Andes mountain range in South America contain a wealth of information on the interplay between climate and tectonics. These areas are characterized by rapid crustal uplifts, high relief, and a variety of climatic regimes; geologic processes are recorded in the form of well-exposed rock units, complex alluvial fans and lake deposits amenable to satellite imaging. Southern California, the San Joaquin Valley, and the Tien Shan in China are characterized by high rates of deformation and complex earthquake fault systems. The Decade Volcanoes are so named by the geological community because they are the most probable sites of catastrophic eruptions in the next decade. The Pacific Rim region in general is particularly vulnerable to large volcanic eruption, strong earthquakes, coastal flooding and other geologic events. The East and South coasts of the US are characterized by rapidly changing coastal geomorphology caused by the interplay of subsidence, sea-level rise, increased urbanization pressure, and severe storm impacts.

These are examples of the areas where NASA will focus process studies and the deployment of airborne and *in situ* measurement facilities in support of future satellite observations. Airborne campaigns with instruments such as AVIRIS, MASTER, and AIRSAR will be conducted on a regular basis for scientific study purposes (annually in the U.S. and once every 3 to 5 years in other areas). The Pacific Rim I campaign, conducted for the first time in 1996, was a cooperative effort among eleven countries and dozens of international organizations. The project deployed the AIRSAR and the Thermal Infrared Multispectral Scanner (TIMS) instruments for studies of volcano, earthquake, and coastal process in Australia, New Zealand and Southeast Asia. A repeat Pacific Rim II campaign is planned in 2000, with an expanded participation and a possible follow-on in 2004. These provide critical data for understanding of geologic phenomena and the development of new observing techniques or algorithms that directly support the analysis, and integration of satellite observations.

In addition, *in situ* observing assets, such as GPS arrays, will be deployed as necessary for monitoring surface deformation over kilometer-scale baselines. Installation of the Southern California Integrated GPS Network (SCIGN) will be completed in 2001 and the network will be evaluated over a period of the next five years. Low-cost GPS arrays are currently being deployed at specific natural laboratories including some active volcanoes, tidal gauge sites in dynamic coastal environments, and other locations. GPS array data will be combined with Interferometric SAR data and other geological and geomorphologic information to understand the basic mechanics of subsidence, volcanism, and shallow earthquake ruptures.

6.3.4.4 Geologic Data Analysis and Modeling

Qualitative descriptions of the action of individual landscape-forming processes (e.g., the evolution of river systems) have been available for some time. More recently, with the influx of synoptic space-based observations, increasingly quantitative models are emerging (e. g., the fractal characteristics of river systems) that incorporate advances in fundamental understanding and provide a coherent basis for assessing the vulnerability to several types of disasters. Landslides triggered by events such as earthquakes, snow melt, or heavy rain are a very serious hazard in many areas. Recent progress in the development of quantitative modeling suggests that NASA offers a unique remote sensing capability to quantify triggered landslide events. Expected progress over a ten-year period, envisions the consolidation of such component models into a generalized model of dynamic geomorphology. While these advances will result mainly from combined research efforts in fundamental geological disciplines (e.g., age dating, petrology, etc.) supported by other funding agencies, any generalized model will also require global data derived from space observations for initialization and testing. Creating productive new methods to facilitate the analysis and interpretation of large data sets is a scientific priority for the next few years. More attention will be given to the development of integrative models capable of assimilating a diversity of *in situ* measurements, remote sensing observations, and laboratory data.

Tectonic models

Models describing the four dimensional variability of accumulated strain (deformation) are key to understanding earthquake source mechanisms. Such models must take into account the rheology (mechanical properties) of the geologic strata under diverse physical and chemical conditions. GPS arrays will provide the first continuous record of strain accumulation, which is the controlling parameter of earthquake frequency in active seismic areas such as southern California. Interferometric SAR observations can provide spatially contiguous data. Using such data acquired throughout the earthquake cycle, it is anticipated that computing strain accumulation in the crust will be possible. The medium-term (5-year) goal will be relating earthquake activity to global deformation patterns, which involves addressing the basic mechanisms of brittle-field deformation.

Volcanic models

Two important objectives are being pursued in volcanic process modeling: understanding how dormant volcanoes become active, and understanding the eruption process itself. The former type of model is needed to assess the vulnerability of several regions to volcanic hazard, some including large cities (e.g., Seattle). The latter is applicable to areas situated within striking distance of volcanoes, to simulate the outcome of potential eruptions. Resurgence of dormant volcanoes, such as Mt. Rainier, is not uncommon and could be extremely costly, given the size of the assets at risk. Such resurgence is the product of deep-seated magma mobilization beneath the volcano, manifested by changes in the local gravity field or topography, both of which can be monitored using space-based techniques. However, current knowledge of volcano resurgence is still tentative and a considerable cooperative effort with other interested agencies will be needed over the next 5 years to develop these models.

Dynamic geomorphology models

This category includes a broad set of models, encompassing diverse aspects of Earth System sciences, that are developed for hazard assessments. Data inputs include dynamic topography (using SAR and laser altimetry), and visible/infrared remote sensing. Coastal erosion and deposition models are intended for predicting the evolution of beaches and coastal wetlands, understanding vulnerability to storms and storm surges, and assessing the usefulness (or lack thereof) of palliative engineering methods. River system evolution models are needed to understand vulnerability to flooding in view of ever-changing land uses, erosion and deposition of sediments by streams. The research strategy over the next 5 to 10 years is to concentrate on the development of individual component models with the objective of integrating these components into future integrated Earth System models.

6.4 LINKAGES

Interagency linkages

NASA's Solid Earth program coordinates research and observational programs with many other US agencies, DOD, and industry. These partnerships are essential, as they provide the foundation for end-to-end research programs, from space flight project development and ground-based studies to data interpretation and modeling. For example, NASA is cooperating with NIMA for the development of the Shuttle Radar Topography Mission (SRTM) and is already generating terrain-related data and gravity field models for civilian and defense surveying applications. NASA is considering, with NOAA and FAA, the means to develop a space-based volcanic ash and SO_2 clouds monitoring program for the protection of air traffic, and is partnering with FEMA and the Army Corps of Engineers for floodplain mapping and modeling.

The proof-of-concept GPS-MET satellite project (1995), sponsored jointly with the National Science Foundation (NSF), demonstrated the capability of a NASA-developed GPS receiver to provide accurate atmospheric temperature and pressure profile measurements in a limb occultation mode. A recent development is the ground-based GPS monitoring of volcanoes; experimental deployment is underway at several sites. The realization and exploitation of the Southern California Integrated GPS Network is another example of a major joint activity with NSF, the US Geological Survey,the Southern California Earthquakes Center, and the Keck Foundation.

NASA will continue to cooperate with other agencies (notably the USGS) and international partners in the implementation of airborne magnetic field measurement campaigns to fill gaps in space-based observations and acquire ground truth data.

The EarthScope Initiative (www.earthscope.org) is an ambitious proposal of the solid Earth research community to significantly advance our understanding of the structure and dynamics of the North American lithosphere. The NSF, USGS and NASA are seeking the means to make EarthScope Initiative (www.earthscope.org) a reality. NASA has stated it’s interest in supporting the Plate Boundary Observatory through it’s on going geodynamics program and will provide the leadership for the development of an InSAR component.

The integrated wide area observations of both time continuous strain measurements of the GPS based PBO and the spatially continuous observations of the INSAR will make significant progress toward understanding the relationship between temporal and spatial variations in crustal strain and the associated risk of earthquake and volcanic eruption. Scientists have observed from continuous GPS arrays such as SCIGN previously unknown phenomena including silent earthquakes or unexpected changes in crustal deformation following earthquakes. Some of these forcings clearly come from water and/or temperature effects, but there is also evidence of tectonic process changes after large earthquakes (e.g. changes in velocity field after Landers). Earthscope will exploit recent advances in GPS and INSAR space geodetic technology to provide Earth scientists with an unprecedented view of crustal deformation and will undoubtly stimulate new insights in the workings of Earth’s crust and advance the predicability of and the response to natural disasters.

International linkages

International cooperation is the normal mode of operation in Solid Earth Science. Over 60 international agreements formalize NASA’s cooperative activities with other countries. NASA is the leading U.S. participant in international programs such as the International Earth Rotation Service, the International GPS Service (IGS), the Continuous Observation of the Rotation of Earth (CORE) program, the International VLBI Service, the International Laser Ranging Service (ILRS), and the International SAR Working Group.

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